ASSESSMENT OF SPONTANEOUS HEATING OF SOME INDIAN COAL USING FIRE RISK INDEX BY CROSSING POINT TEMPERATURE METHOD

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Assessment of Spontaneous Heating of Some Indian Coal Using Fire Risk Index by Crossing Point Temperature Method

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By

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based on research carried out

under the supervision of

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Supervisors' Certificate

This is to certify that the work presented in the dissertation entitled "*Assessment of Spontaneous Heating of some Indian coal using Fire Risk Index by Crossing Point Temperature Method"* submitted by *Neelabh Abhishek*, Roll Number 112MN0424, is a record of original research carried out by him under our supervision and guidance in partial fulfilment of the requirements for the degree of *Bachelor of Technology* in *Mining Engineering*. Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

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Declaration of Originality

I, *Neelabh Abhishek*, Roll Number *112MN0424* hereby declare that this dissertation entitled *"Assessment of Spontaneous Heating of some Indian coal using Fire Risk Index by Crossing Point Temperature Method"* presents my original work carried out as an undergraduate student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this thesis have been duly recognized under the sections "Reference". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

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May 16, 2016

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Abstract

For many years it has been seen that mine fires are the leading and primary cause for the loss of life and property particularly in this sector and leading to these issues, spontaneous heating or self-ignition or auto-oxidation of coal is one of the major issues. Since the properties of coal varies from place to place because of different theories of the formation of coal. Therefore, researchers, academicians, field engineers and scientists have carried out experimental investigation in India and other countries and derived various methods for finding out the susceptibility of coal to spontaneous heating.

In India, various techniques like Crossing point temperature method, Olpinski index, DTA, Wet oxidation, etc. are being used to determine the coals susceptibility to spontaneous heating. Here, crossing point temperature method is commonly adopted technique to determine the rate at which coal gets to fire. Fire risk index is also being calculated from the inflection point and crossing point temperatures observed from the graph.

Crossing point temperature is the temperature at which both the bath temperature and coal temperature coincides. In this method, bath is continuously heated at 1˚C/min. This approach has many advantages as it is less costly and is very easy to handle. After determining various crossing point temperatures and inflection point temperatures, MR index was calculated to assess the susceptibility of Indian coals to spontaneous heating.

Keywords: *Spontaneous heating, Crossing point temperature, fire risk*

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Chapter 1

Introduction

1.1. Background

Coal can be said as “Ancient Gift Serving Modern Man.”

Around 300 million years back, plants and trees developed in marshes and swamps secured a significant part of the earth. Around 300 million years back, plants and trees grew in swamps that covered much of the land and terrain. After the vegetation died and the build-up of silt as well as other sediments, together with “tectonic movements” would bury these swamps and peat bogs, often to great depths. With burial, the plant material would be subjected to high temperatures and pressures generated by the tectonic forces in the Earth. This would cause physical and chemical changes in the vegetation, transforming it over time into peat and ultimately into coal [1].

The issue of “spontaneous heating” has been connected with coal mining from the day mining began. Prior, it was viewed as that much warming was connected with just certain sorts of coal yet now it has been seen that it has affected the entire coal mining sector. Much research work has been done on this important subject, and more is going on other aspects of underground mine fire are yet to be altogether comprehended and the status of our knowledge on “spontaneous heating” is a long way from complete.

“Spontaneous heating” is considered as the fundamental cause of mine fires, and it constitutes more than half of such fires. Besides the waste of valuable coal, such fires also pose a danger to lives. From an economic point of view, even a small incident of spontaneous heating can take a heavy toll regarding the loss of production, loss of machinery and expenses incurred in fighting it out. Around seventy percent of coal is being used for the generation of electricity in India, and thus, utmost care should be taken for the prevention of mine fire caused from spontaneous heating [2].

It has also been seen that low-rank coal with high oxygen content and coal containing more vitrain and clarain, high moisture content and many other factors are responsible for the spontaneous heating of coal. Apart from these, geological and mining conditions also lead to spontaneous heating. The incubation period for high-rank coal varies from six to nine months [3**].**

Since the properties of coal vary from place to place it is tough to determine and understand the mechanism of spontaneous heating. Different research works and experiments are being carried out by various nations to measure the heating tendency of the coal. Various methods like Crossing Point Temperature (CPT) in India, Russian U-index in Russia, Olpinski index in Poland, Adiabatic Calorimetry in U.S.A., etc. have been established to find out the heating rate of coal [10].

Alternate techniques endeavoured by scientists are Differential Thermal Analysis [14], Wet Oxidation method [16], Gas Indices studies [17], etc. In any case, there is no unanimity amongst researchers for the appropriation of a particular strategy for the evaluation of spontaneous heating susceptibility of coals. Truth be told, scientists have proposed that various methods that might be endeavoured to decide precisely the susceptibility of coal to spontaneous heating [4, 10].

1.2 Objective of the dissertation

Keeping the above points in mind, the present work has been planned with the following objectives

- Determination of crossing point temperature of collected coal samples.
- Determination of MR liability index.
- Establish the co-relation between crossing point temperature and liability index

Chapter 2

Literature Review

2.1 National and International Status

The following is the brief survey of the work carried by various scientists and investigators to decide the susceptibility of coal to spontaneous heating.

Banerjee (1972) determined the "Crossing Point Temperature (CPT)" for various Indian coal samples following the "Crossing Point Temperature method." He observed that coals with crossing points temperatures between 120°C & 140°C could be considered to be highly susceptible to spontaneous heating and those above 160°C are less susceptible to self-oxidation. And the temperature ranging between 140°C and 160°C are deemed to be moderately susceptible to spontaneous heating.

Nandy et al. (1972) pointed out certain limitations for crossing point temperature method for coal samples having more moisture content. They suggested that the crossing point temperature usually decreases with increase in moisture content, volatile matter and oxygen content and also with the reduction of the carbon content in the coal sample. They also suggested that beyond 4-6% moisture content, CPT again exhibits an increasing trend [5].

Feng et al. (1973) developed a composite liability index using the results of Crossing Point Temperature experiments, called FCC index. This is calculated using the following equation:

$$Liability\ index = \frac{Average\ heating\ rate\ between\ 110^{\circ}\text{C and } 220^{\circ}\text{C}}{Relative\ Ignition\ Temperature} \times 10 \text{ ………. (2.1)}$$

They selected 110˚C as the lower limit for the heating rate to ensure that all the moisture had evaporated from the sample. The upper limit of 220˚C was chosen as there would have been a little evolution of volatile matter below this temperature [6].

Mahadevan and Ramlu (1985) objected to the arbitrary selection of temperature ranges in the FCC index and proposed an index known as MR index as:

$$Liability\ index = \frac{Average\ heating\ rate\ between\ \text{the inflection and crossing points}}{Time\ to\ reach\ the\ inflection\ point} \times \frac{Time\ to\ reach\ the\ crossing\ point}{Heating\ rate\ at\ the\ crossing\ point} \times 10 \quad (2.2)$$

Panigrahi et al. (1997) directed examinations for the determination of Russian U-index. Ten coal specimens from Jharia coalfields have been analysed by this method. The carbon, hydrogen, nitrogen, and sulfur substance for these specimens were determined by utilizing Fenton's technique for ultimate analysis. Notwithstanding this, the crossing point temperature of these specimens was likewise decided. At that point, correlations were made corresponding to the Russian index and CPT of coal tests with its fundamental constituent's viz. carbon, hydrogen and ash content. It has additionally been watched that from the purpose of the vulnerability of self-ignition of coal, Russian U-index, demonstrates a similar connection with the essential constituents of as the crossing point temperature, which may turn out to be a helpful strategy for coal classification in Indian circumstances.

Mahidin et al. (2002) also observed somewhat similar results. They further related their work increase in oxygen and volatile matter contents in coal. They also observed a good correlation between FTIR and CPT data [5].

Kadioglu and Varamaz (2003) investigated the consequence of moisture content and air-drying on spontaneous combustion of coal using CPT method and established that CPT values increased as moisture and particle size of the coal sample increases [5]. They stated that the reciprocal of their index is increased with self-heating liability [11].

Nimaje et al. (2010) determined thermal studies on spontaneous heating of coal. Thermal studies play a significant role in determining the susceptibility to auto-oxidation of coal. They made a review of thermal studies did by various researchers and scientists over the globe for determination of spontaneous heating of coal and uncovered that part of stressed on trial systems is essential for developing suitable methodologies and compelling arrangements ahead of time to anticipate event and spread of fire.

Xuyao Q et al. (2011) investigated the crossing point temperature (CPT) of different coal ranks of coal by using a self-designed experimental system. Coal particles ranging from 0.18 mm to 0.38 mm in size and weight of 50 g of coal specimens were put in copper reaction vessel attached to the centre of a temperature programmed enclosure. The heating rate was maintained for 0.8˚C/min. The results indicated that rank of coal, moisture, sulphur and experimental conditions affect the crossing point temperature. Drying at 40˚C reduces the effect of moisture for samples that contain high moisture content [19].

Choi et al. (2012) investigated on a comparison of spontaneous combustion susceptibility of coal according to its rank. For this investigation, both crossing point temperature method and gas chromatography were performed. Lignite and bituminous coals were used to perform the experiments. It was observed that lignite was more easily oxidised than bituminous coal at a low temperature which resulted in more oxygen consumption, increase in CO and CO_2 generation and low CPT. It was also observed that even though the coal may have the same rank and CPT, spontaneous combustion susceptibility of coal may vary because the initial temperature of the coal at which oxidation begins may be different due to the substances that participate in oxidation [21].

Xuyao Q et al. (2013) investigated the effects of sulphur components on crossing point temperature of coal. The results indicated that the effects of sulphur components depend on the rank of the coal and also on the reaction conditions. The reactivity of coal is low under dry and low-temperature conditions. They also found that the sulphur components form a film that covers the coal surface and slightly inhibits self-heating of coal

Wantaek et al. (2015) investigated the changes in spontaneous combustion susceptibility of low-rank coal through pre-oxidation processing at low temperatures. Physical properties of coal and changes in crossing-point temperature (CPT) caused by the pre-oxidation processing were also analyzed. Higher the temperature for pre-oxidation, the more consumption of O_2 gas in coal, and a larger increase in temperature of the coal was observed. From these results, it was confirmed that the spontaneous combustion susceptibility of the coal can be suppressed without a significant reduction in weight and calories through the pre-oxidation processing of low-rank coal under the proper conditions [20].

2.2 Factors affecting spontaneous heating of coal

Many factors are affecting the self-ignition of coal. It has been seen that seams which catch fire are mostly beside the seams worked by the same method. In this part, the impact of all the components of spontaneous heating of coals is talked about. The occurrence of spontaneous combustion, however little, if not managed successfully and productively in the early stages can form into open flames or a blast of gas, with catastrophic results.

The factors [6, 8] affecting the susceptibility of coal to spontaneous heating are given below:

2.2.1 Surface Area of Coal

If we see the coal structure deeply, lots of pores can be observed. It has also been seen that the amount of heat liberated depends on the total surface area of the coal including the internal surface area due to its structure. If the entire pore surface is greater than 80 m^2/g, it will form a reaction site. Peters observed that free diffusion took place in macropores below 10^{-5} mm in size. **Munzer and Peters** stated that, at low temperatures, for particle size less than 0.3 mm in size the oxidation rate were practically same, but significant amount of deviation was observed for particle size greater than 0.5 mm size.

2.2.2 Coal Rank

Higher rank coal is less susceptible to spontaneous heating, and lower grade coal is more susceptible to spontaneous heating. Lower grade coal contains more moisture, volatile matter, and oxygen.

2.2.3 Volatile Content

It has been found that high volatile coals are more susceptible to spontaneous heating than low volatile coals. VM greater than 18% is considered to be high volatile coals and also oxidise faster.

2.2.4 Petrographic Composition of Coal

Earlier, it was not sure that petrographic composition of coal influenced susceptibility to spontaneous heating. By the time, it has been accepted that the ease of oxidation of coal decreases with the macro constituents in the order: Vitrain, Clarain, Durain, and Fusain.

2.2.5 Oxygen Content

Even though the heating rate is not in all cases proportional to the oxygen content, increased reactivity of low-rank coals is attributed to their higher original oxygen content.

2.2.6 Moisture Content

The oxidation of coal in the air and ambient temperatures takes place practically in the presence of moisture present in the atmosphere, moisture present in the coal, or formed through oxidation. The exact process of the moisture on the coal sample and spontaneous heating of the coal are still unknown.

2.2.7 Presence of Pyrite

Iron pyrites commonly occur in coal seams as distinct and separate particles in a wide range of shapes and sizes. It readily oxidises at ordinary temperature in moist air. According to Munzner, the heat change caused by oxidation is same for coal and pyrite in the dry state and the reactivity of coal is only doubled when wet. The oxidation of pyrite in the presence of free moisture has only a prompting effect on auto-oxidation of coal when present in concentrations greater than 3%.

2.2.8 Ash Content

Ash content in the coal generally reduces the oxidation rate but may be influenced to some extent by the mineral composition of the ash.

2.2.9 Temperature

Temperature plays a significant role in oxidation rate. Lower temperature favour accumulation of oxygen on the coal and at higher temperature >70˚C, gaseous oxidation products are released.

2.2.10 Freshness of exposed coal surface

Coals which are freshly exposed consume more oxygen at a relatively higher rate, which falls off continuously with time during the progress of oxidation for given set of constant conditions.

2.3 Contributing Factors for spontaneous combustion of coal in mines

There are several other factors which contribute to the spontaneous combustion of coal in mines other than intrinsic properties. These can be grouped under two main heads: geological and technical factors [6].

2.3.1 Geological Factors

- Seams greater than 3m thick pose a great hazard due to crushing of coal under rock pressure, high losses of coal during extraction, higher geothermic gradients in deep mines
- In zones of tectonic disturbances such as faults, leakage of water and air takes place
- Contiguous seams pose more threat to spontaneous combustion
- Carbonaceous shales in the roof of coal seams may also lead to fires

It has been seen that the geological factors are uncontrollable.

2.3.2 Technical Factors

- Extensive development in coal seams will expose large area of the coal which leads to leakage of air currents and oxidation
- It has been seen that high rate of extraction is the best guarantee against the incidents of fire against coal seams
- Caving under shallow overburden cover may produce cracks reaching up to the surface, which leads to leakage of air currents from the surface to the underground
- Ventilating pressure may also be checked while working underground as it should not result in any air leakage that may cause oxidation of coal
- Mining of contiguous seams and thick seams in slices may also lead to air leakage and should be controlled

It has been seen that the technical factors can be controlled.

2.4 Stages of oxidation and spontaneous combustion of coal

The oxidation of different coal samples have been extensively investigated using thermogravimetric and thermos-volumetric oxidation tests at low and high temperatures under isothermal conditions, but because of the diversity in coal substances and experimental conditions, one could draw only a few general conclusions out of the quite contradictory results [6].

After lot research work done and accepted the simplified view of complex low-temperature oxidation reactions, all coal reacts in same basic manner. Oxygen complexes are formed at different temperatures as a result of saturation at these temperatures of the unsaturated constituents of coal with the release of some gaseous products. In first few hours, a major portion of oxygen is being absorbed by coal. Immediately after oxidation, both CO and CO_2 are evolved. It has been seen that chemical oxidation of coal releases more heat than physical adsorption of oxygen. Beyond 40˚C, CO is issued at an increasingly rapid rate [6].

Temperature range between 50˚C and 100˚C, the oxidation rate accelerates significantly due to sustained exothermic reaction and ultimately produces flaming combustion or ignition within the temperature range between 327˚C to 420˚C for bituminous coal.

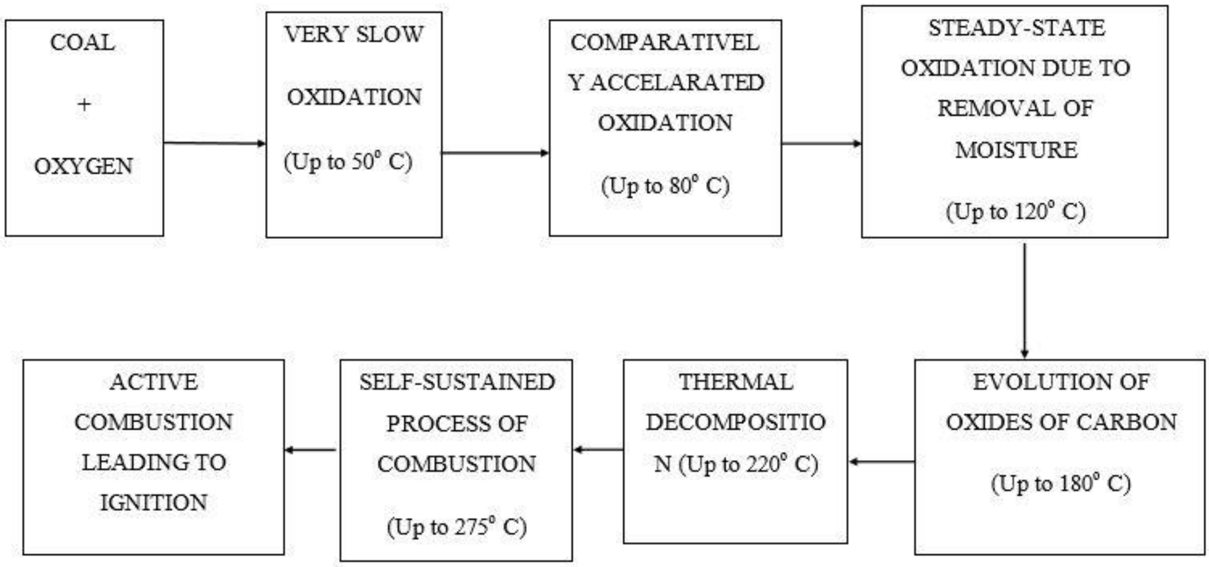

Fig. 2.4.1 Stages of Spontaneous Heating of Coal [18]

Also, there are three distinct stages of combustion of coal in coal mines:-

- The incubation period
- The indication period
- Open fire

From the practical point of view, the incubation period is said to denote the period between the first roof fall after beginning of the coal extraction in a district or panel and the appearance of first signs of heating. Seam thickness method of working, a method of roof control, continuity of work, etc. are some of the factors responsible for the incubation period [6].

After the incubation period comes the indication period. Indication period lasts for only a few hours and has a very short span of time. It is marked by sweating, and haze in the air, caused by warmed up air from fire coming into contact with cooler coal or rock [6].

In the end, open fire breaks out. The ‘fire stink’ can easily be recognised by the characteristic petrolic smell [6].

Chapter 3

Experimental Investigation

Different techniques have been used in the laboratory for the study of spontaneous combustion of coal. Most of the methods are based on the measurement of oxidation rate and ignition temperature. This report deals with the temperature differential method viz. Crossing point temperature method [9].

3.1 Collection and Preparation of Sample

3.1.1 Channel Sampling

A sampling of coal in situ gives the measure of the quality of coal to be mined. The section of the seam to be sampled should be fully exposed i.e. from floor to the roof. The rectangular channel should be cut. Therefore, the surface should be smooth. Dimensions of 30 cm width and 10 cm depth should be cut for taking out the sample from the seam. Dirt bands greater than 10 cm should be excluded [14].

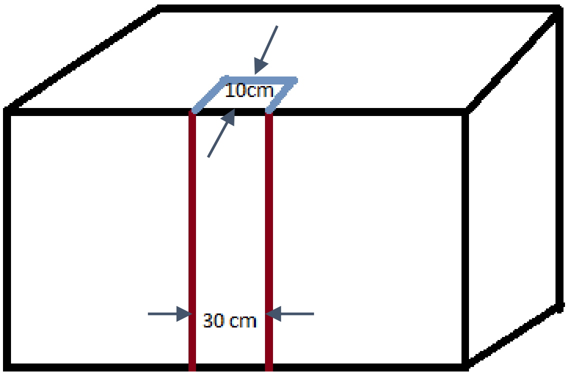

Fig 3.1.1 Channel Sampling of Coal Seam in situ [14]

3.2 Method for Determining Spontaneous Heating of Coal

There are different methods used for determining the susceptibility to spontaneous heating of coal i.e. Crossing point temperature, Wet oxidation method, DTA, Olpinski index method.

3.2.1 Crossing Point Temperature method

This method was used to determine the spontaneous heating of coal and is one of the oldest methods. Here, the bath temperature is allowed to rise at a constant heating rate at 1˚C/minute, and 4 grams of coal sample was taken of -100 +200 mesh BSS. Oxygen at a rate of 80 ml/minute should be allowed to flow through the drying tower. The regulator was used to control the flow rate of oxygen and helps to maintain the flow at a constant rate. The commonly used apparatus is shown in the figure 3.2.1 [12].

Fig. 3.2.1 Crossing Point Temperature apparatus

The fire risk of the coal samples can be established using Table 3.2.1. It shows that crossing point temperature greater than 160 ˚C are poorly susceptible to spontaneous heating and crossing point temperature ranging between 140-160˚C are moderately susceptible to spontaneous heating and crossing point temperature below 140˚C are highly susceptible to spontaneous heating [6].

Table 3.2.1 Classification of coal based on Crossing Point Temperature [6]

CPT (˚C)	**Risk Rating**
120-140	Highly susceptible
140-160	Moderately susceptible
>160	Poorly susceptible

The following represents the procedure to be carried out for determination of crossing point temperature method [7]:

- Collection of coal samples from different mines using channel sampling;
- Sample is prepared for experimentation purpose;
- Sample of size of -100 +200 mesh BSS are taken;

- 4 grams of coal sample is taken and placed in a reaction tube followed by glass wool;
- The tube is placed in the furnace covered with chromel-alumel thermocouple inserted in between the sample and the tube;
- The knob of oxygen cylinder is opened so that accumulated gases are being removed for few minutes;
- Oxygen flow of 80 ml/min is maintained;
- Heating rate of 1˚C/min is maintained;
- Inflection point, crossing point and liability index is determined;

3.2.2 Mahadevan and Ramlu Index

From the Fig. 3.2.2, we can see that the curve 'abcd' depicts the heating rate of the coal sample. As we can see from the graph that the temperature decreases at first and then it found out to be parallel and then the temperature suddenly rises and crosses the bath temperature. Researchers consider point b in the above figure to be more important than a crossing point because after this temperature the sample can overtake the bath temperature.

The graph between time and temperature is known as a heating curve. The heating curve analysis of coal is given in Fig. 3.2.2.

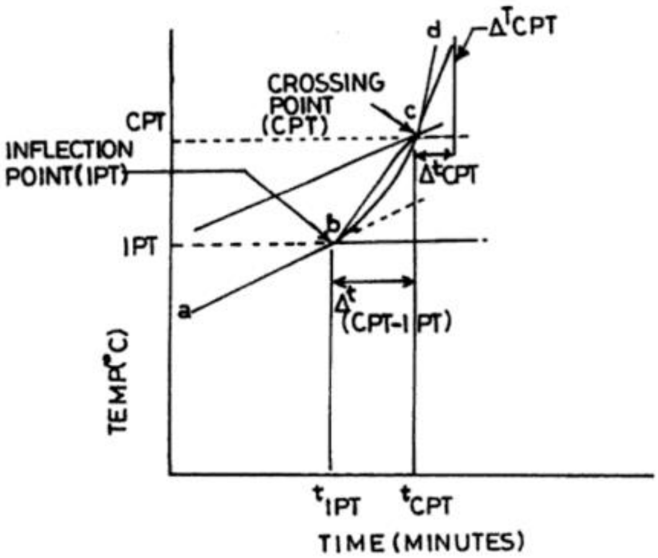

Fig 3.2.2 Heating curve analysis of coal [6]

In the Fig. 3.2.2 x-axis represents the time in minutes and y-axis represents the temperature in ˚C.

- 't_{IPT}' represents the time at the Inflection Point Temperature.

- 't_{CPT}' represents the time at the Crossing Point Temperature.
- '$\Delta t_{CPT\text{-}IPT}$' represents time difference between Crossing Point Temperature and Inflection Point Temperature.
- 'Δt_{CPT}' represents the time difference between points 'cd.'
- 'ΔT_{CPT}' represents the temperature difference between the point 'cd.'
- '$\Delta T_{CPT\text{-}IPT}$' represents the temperature difference between CPT and IPT

$$Liability\ index = \frac{Average\ heating\ rate\ between\ \text{the inflection and crossing points}}{Time\ to\ reach\ the\ inflection\ point} \times \frac{Time\ to\ reach\ the\ crossing\ point}{Heating\ rate\ at\ the\ crossing\ point} \times 10 \quad (3.2.1)$$

Mahadevan and Ramlu (1985) identified three different stages in crossing point temperature curve which is as follows:

1. Inflection Point – It is the point when exothermicity is first noticeable, and it can be observed from natural observation and graph.
2. Crossing Point – It is that point when the coal temperature and bath temperature are equal.
3. Ignition Point – It is the minimum temperature from where the combustion takes place or is supposed to happen.

Based on the calculations carried out by the findings of crossing point temperature and inflection point temperature, the fire risk classification of coal is depicted in table 3.2.2.

Table 3.2.2 Fire risk classification of coal based on Crossing Point Temperature [6]

Liability index of coal	Susceptibility to spontaneous heating
0-5	Low
5-10	Medium
>10	High

Chapter 4

Results and Analysis

The crossing point temperature of all the coal samples are determined using the CPT apparatus in an air medium, and the table below shows the crossing point of different samples:

Table 4.1 Results of CPT

SL. NO.	Sample	Crossing Point Temperature (˚C)
1.	MCL-1	108
2	MCL-2	112
3.	MCL-3	132
4.	CCL-1	160
5.	CCL-2	158
6.	CCL-3	183
7.	CCL-4	207
8.	CCL-5	200
9.	CCL-6	170
10.	CCL-7	176
11.	CCL-8	183
12.	MCL-4	156
13.	CCL-9	189
14.	MCL-5	174
15.	MCL-6	176
16.	MCL-7	180
17.	MCL-8	167
18.	MCL-9	181
19.	MCL-10	180
20.	MCL-11	132

The MR index of different coal samples was calculated from the crossing point and inflection point temperatures and is listed in Table 4.2.

Table 4.2 Liability Index of Different Coal Samples

SL. NO.	Sample	Crossing Point Temperature (˚C)	Inflection Point Temperature (˚C)	MR Liability Index
1.	MCL-1	108	65	13
2	MCL-2	112	67	11.3
3.	MCL-3	132	70	17.9
4.	CCL-1	160	145	10
5.	CCL-2	158	144	9
6.	CCL-3	183	167	5
7.	CCL-4	207	154	4
8.	CCL-5	200	169	2
9.	CCL-6	170	150	3.6
10.	CCL-7	176	150	3.5
11.	CCL-8	183	156	2
12.	MCL-4	156	131	8
13.	CCL-9	189	168	4
14.	MCL-5	174	148	4.5
15.	MCL-6	176	145	4
16.	MCL-7	180	143	3
17.	MCL-8	167	140	4
18.	MCL-9	181	162	3.5
19.	MCL-10	180	148	3
20.	MCL-11	132	80	15

The various CPT curves of the above sample are depicted in Appendix-1.

The relation between crossing point temperature and liability index was established and is shown in Fig. 4.1. The coefficient of determination (R^2) was found out to be 0.7717 which is found to be good. when R^2 is 1, it represents a fit graph [15].

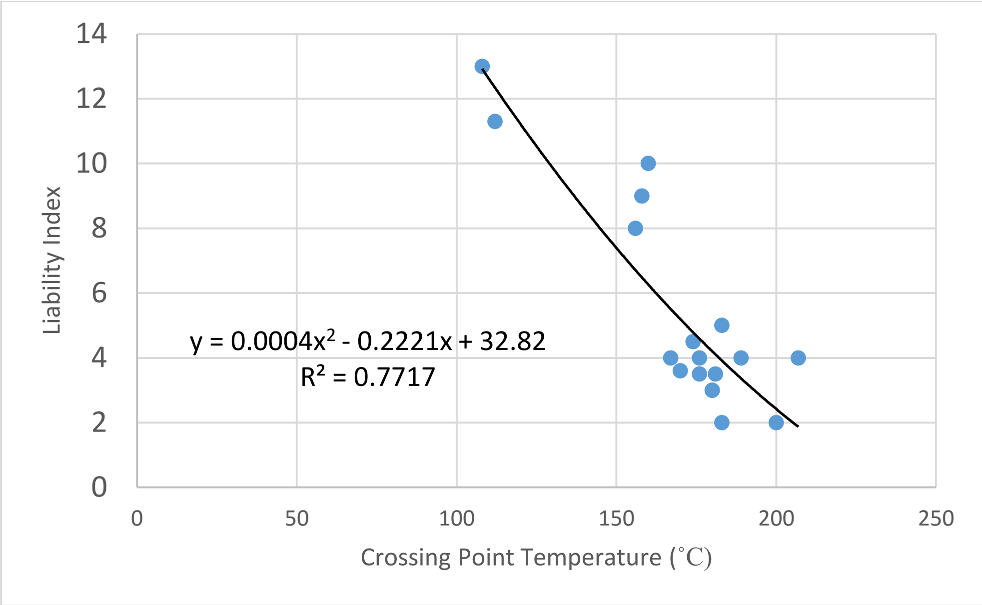

Fig. 4.1 Co-relation between liability index and crossing point temperature

The equation was found out to be:

$$y = 0.0004x^2 - 0.2221x + 32.82 \tag{4.1}$$

Chapter 5

Conclusions

The following conclusions can be drawn from the experimental investigations carried out in this thesis:

- From the above results and analysis, the samples can be categorised according to their susceptibility to spontaneous combustion:

Sl. No.	Fire Risk	Sample Name
1.	High	MCL-1, MCL-2, MCL-3, MCL-11
2.	Medium	CCL-1, CCL-2, MCL-4
3.	Low	CCL-3, CCL-4, CCL-5, CCL-6, CCL-7,CCL-8, CCL-9, MCL-5, MCL-6, MCL-7, MCL-8, MCL-9, MCL-10

- The regression analysis was carried out between crossing point temperature and the liability index and the good correlation (R^2 = 0.7717) was obtained among them. The results were matched with the field record. The final equation is obtained as

$$y = 0.0004x^2 - 0.2221x + 32.82.$$

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APPENDIX -1

CPT CURVES

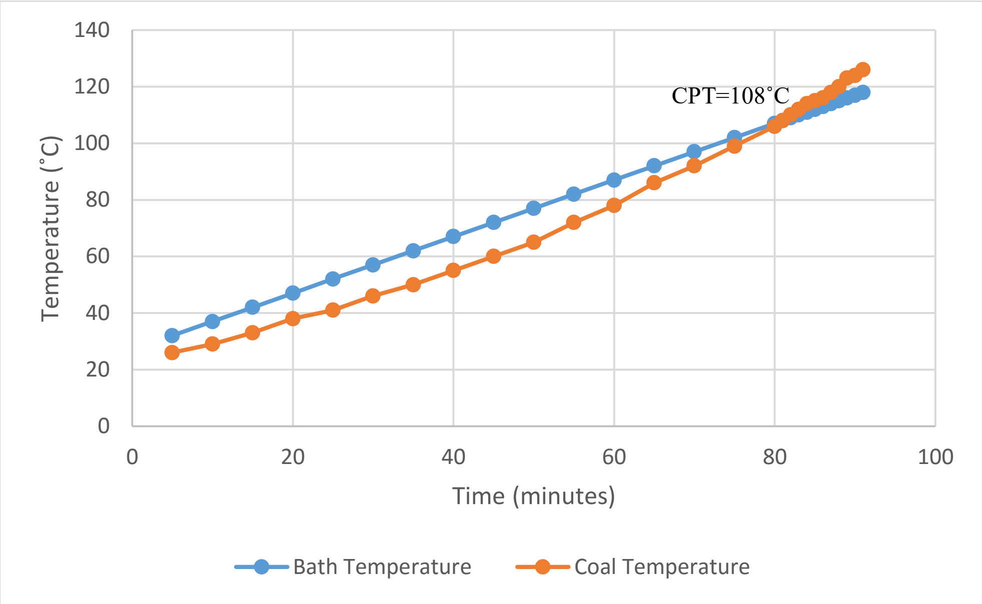

Fig. A-1 CPT curve of MCL-1

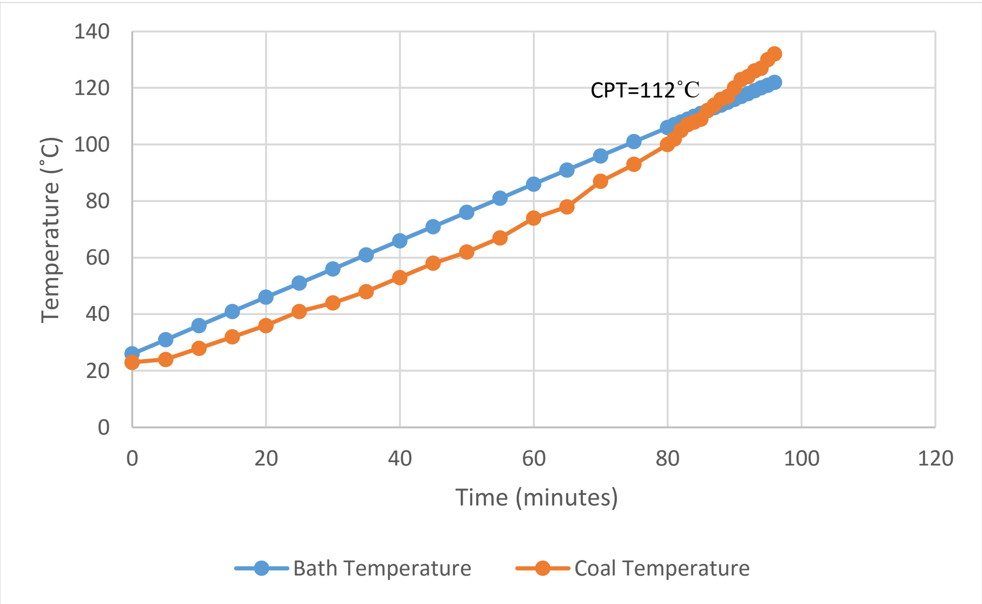

Fig. A-2 CPT curve of MCL-2

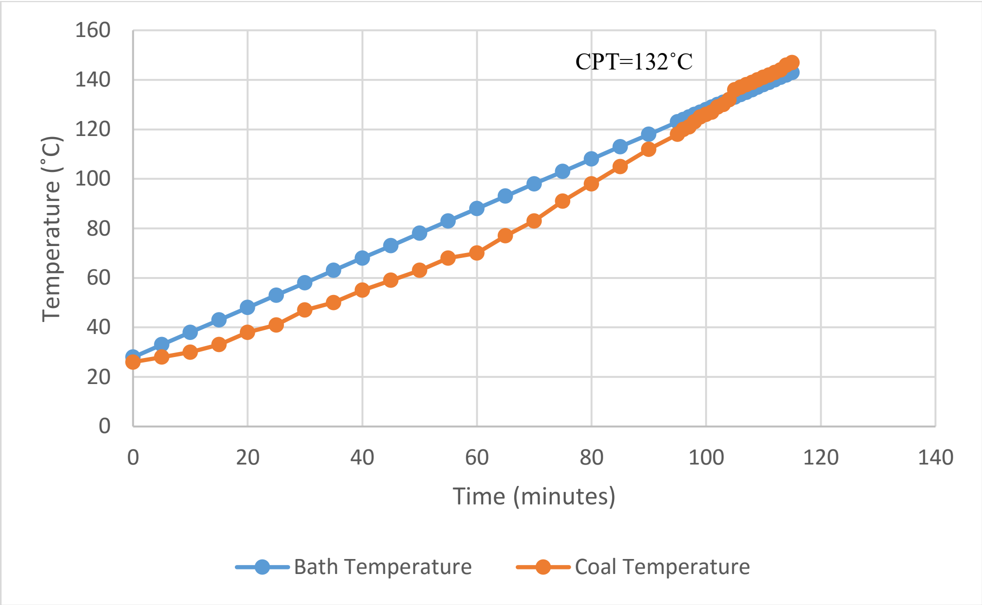

Fig. A-3 CPT curve of MCL-3

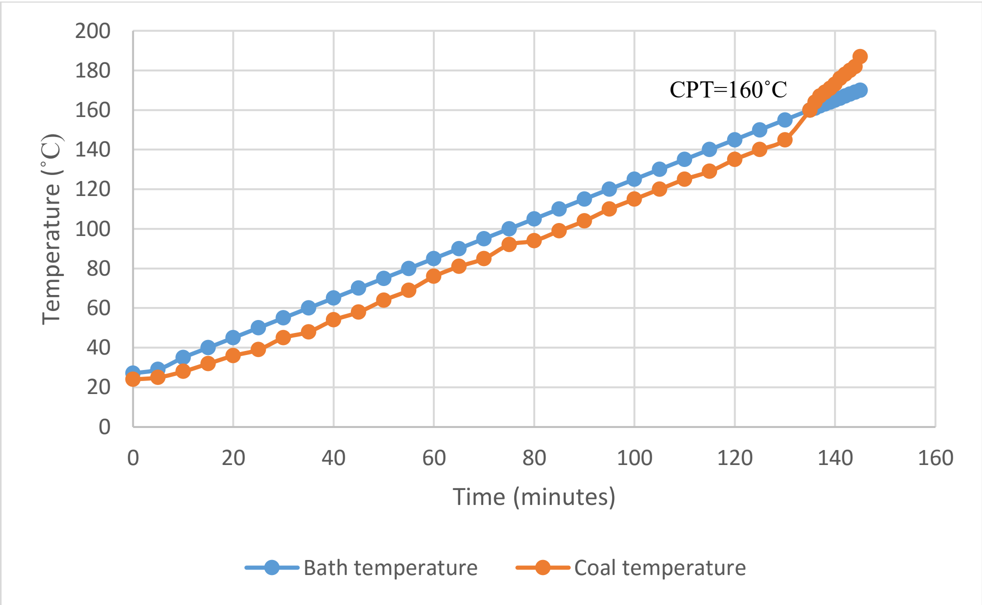

Fig. A-4 CPT curve of CCL-1

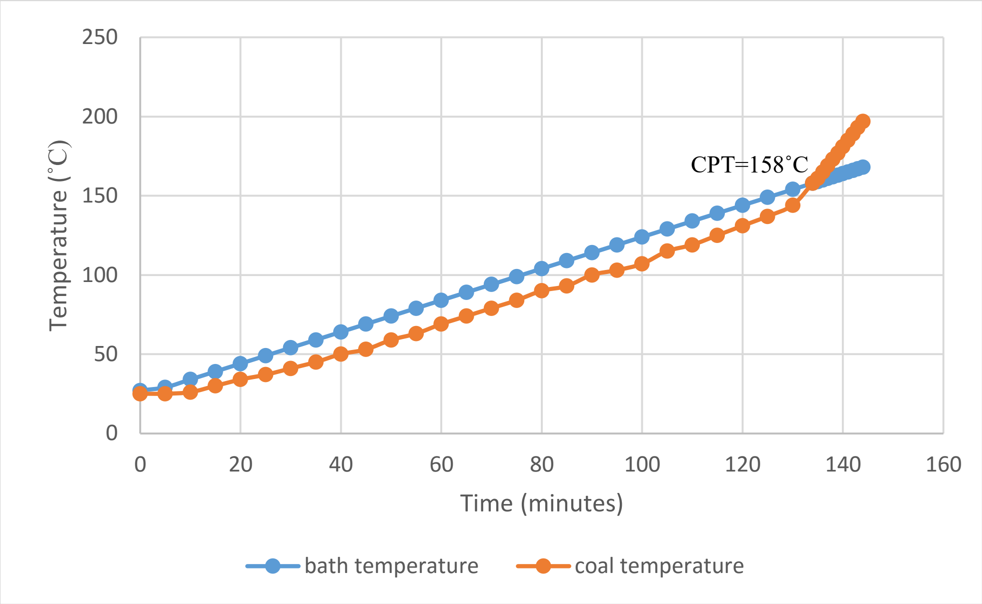

Fig. A-5 CPT curve of CCL-2

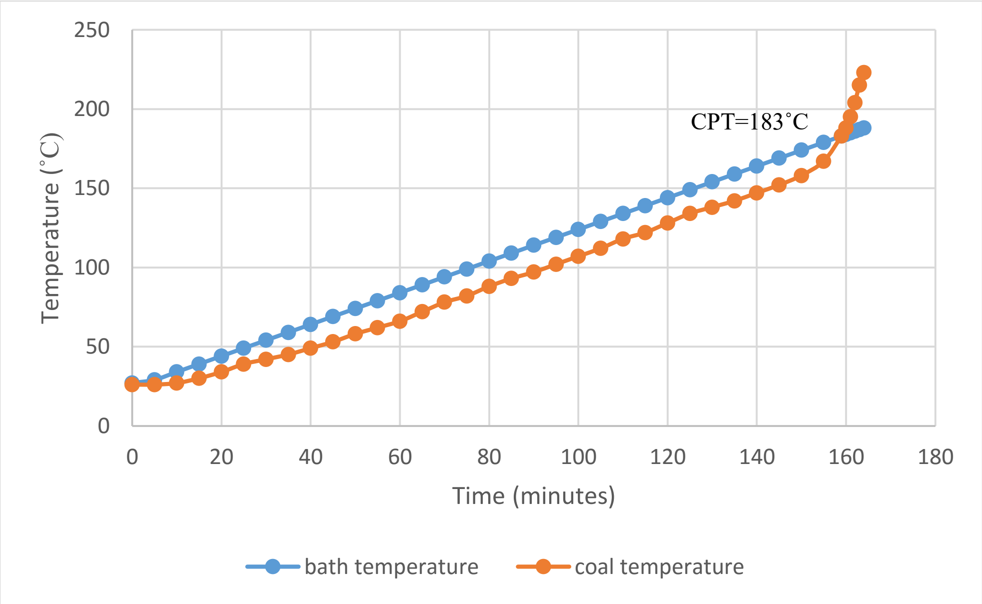

Fig. A-6 CPT curve of CCL-3

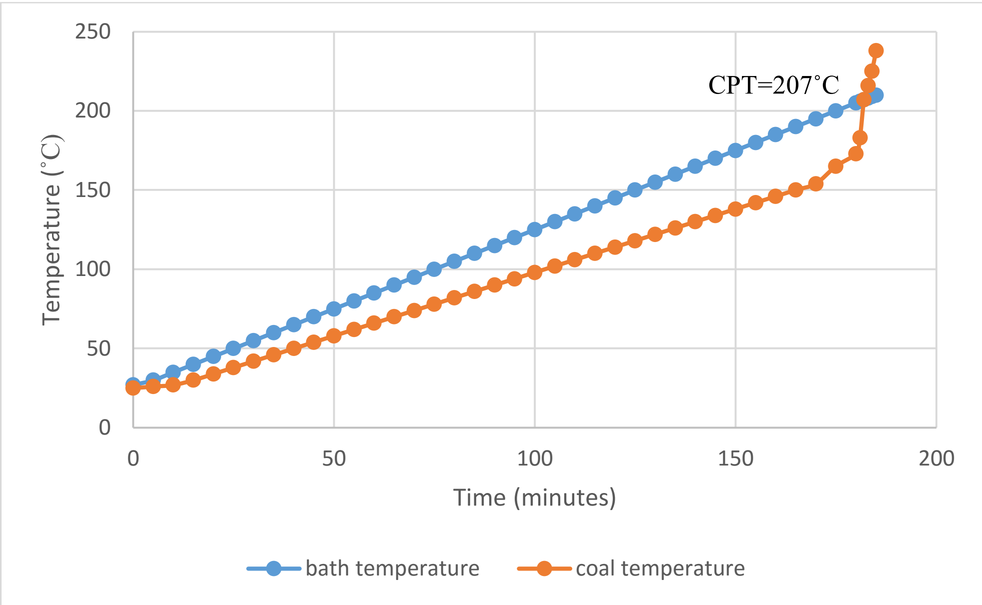

Fig. A-7 CPT curve of CCL-4

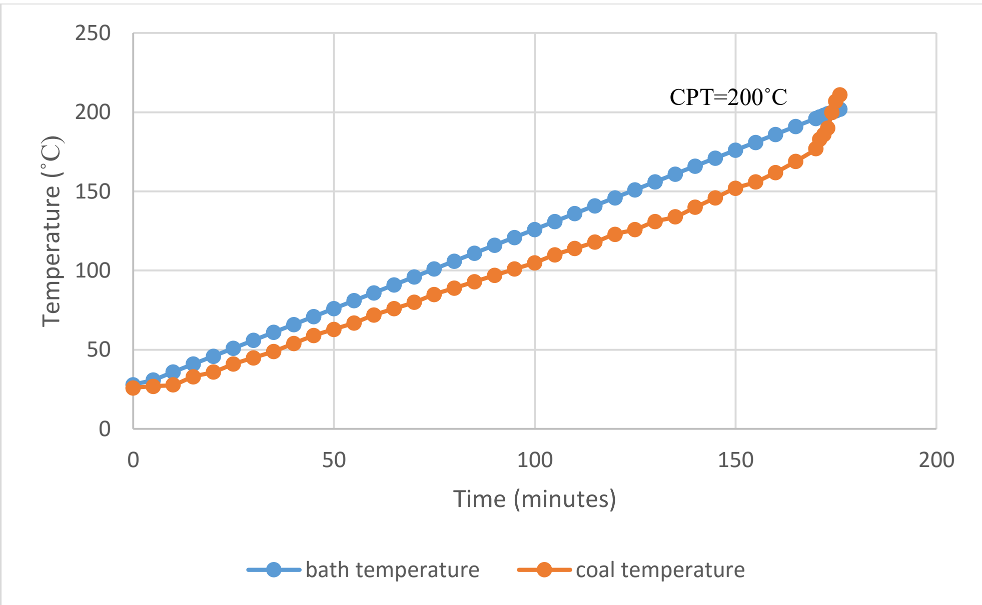

Fig. A-8 CPT curve of CCL-5

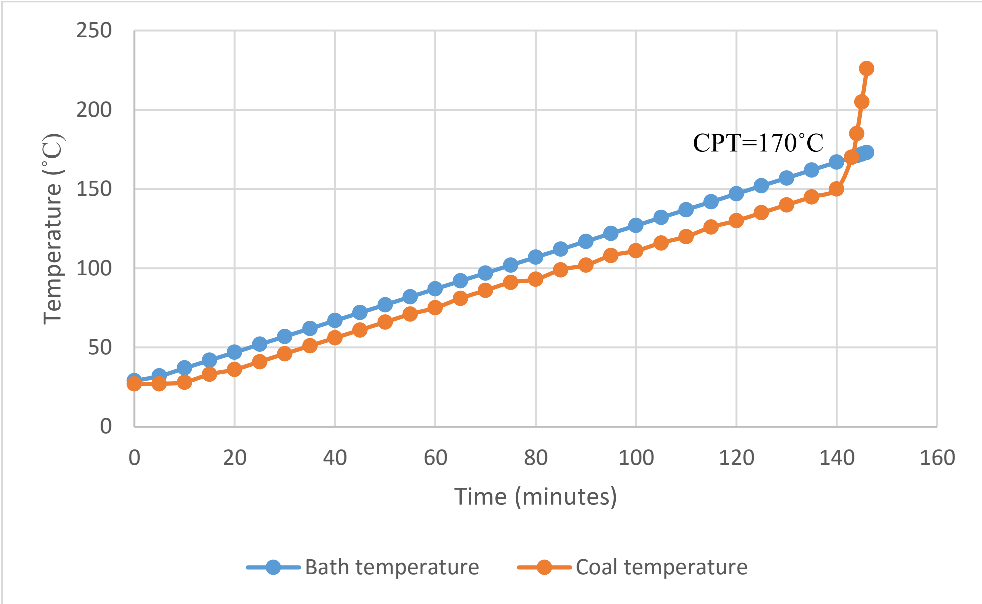

Fig. A-9 CPT curve of CCL-6

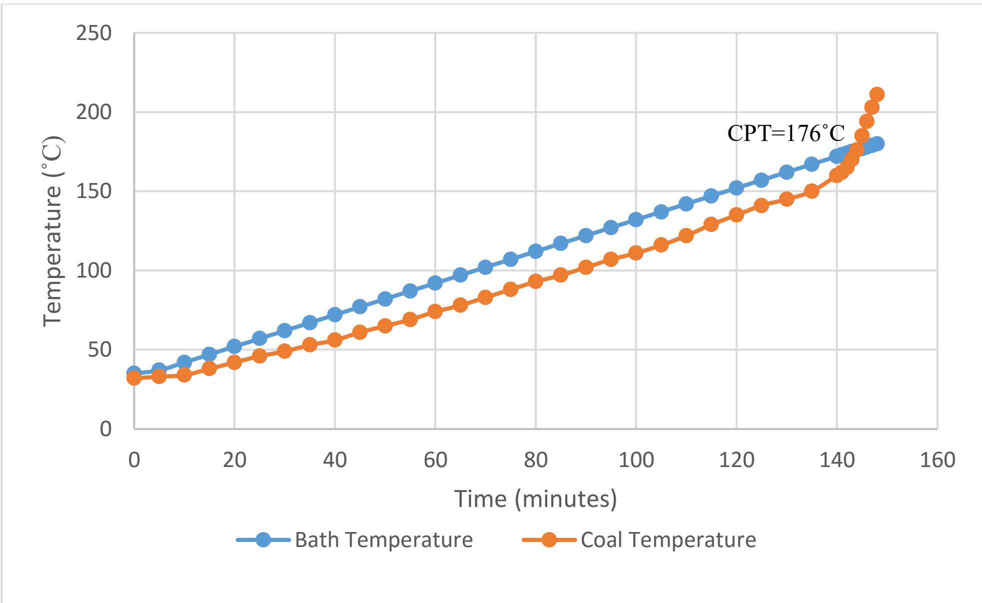

Fig. A-10 CPT curve of CCL-7

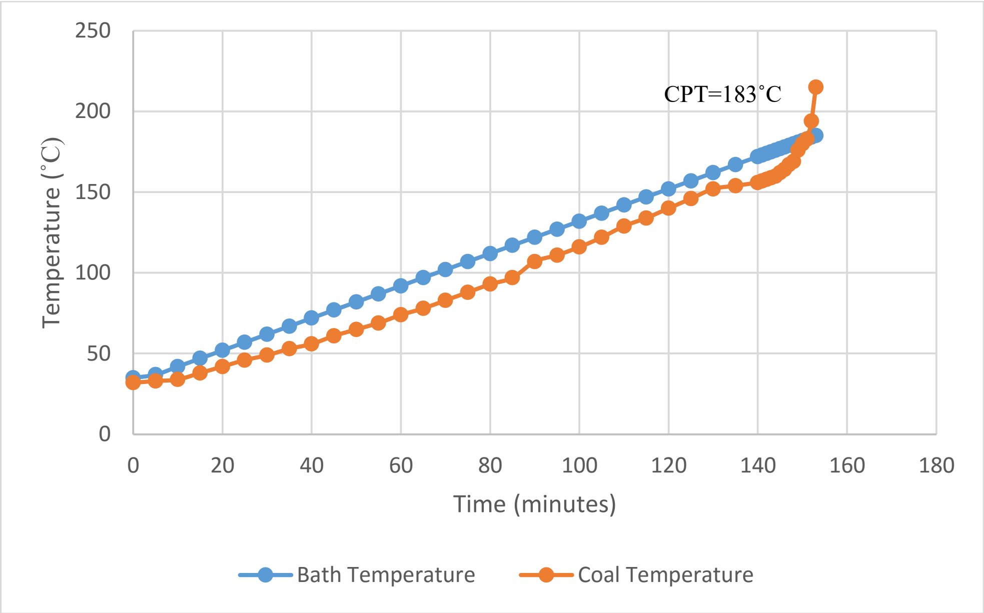

Fig. A-11 CPT Curve of CCL-8

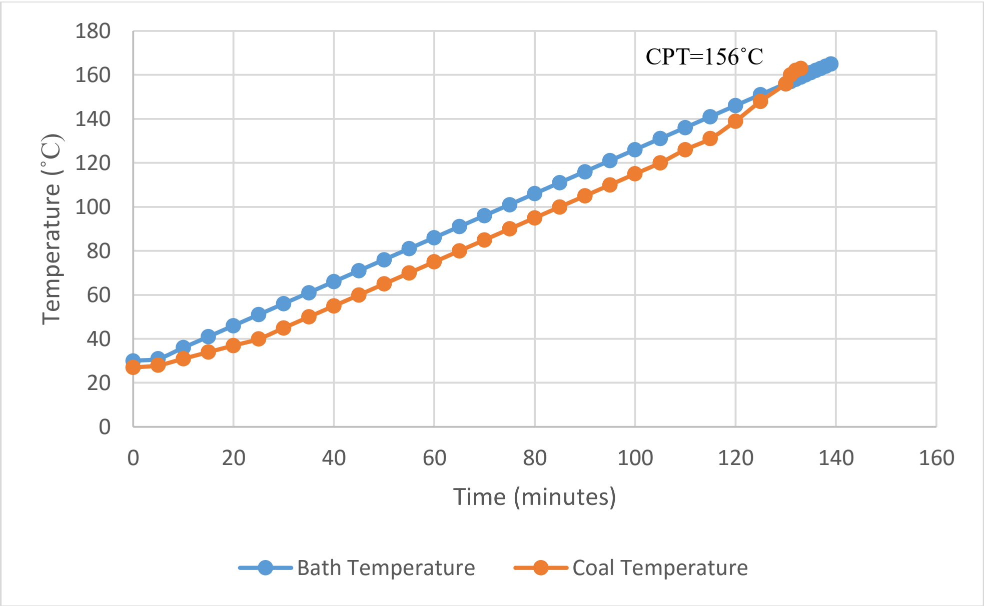

Fig. A-12 CPT Curve of MCL-4

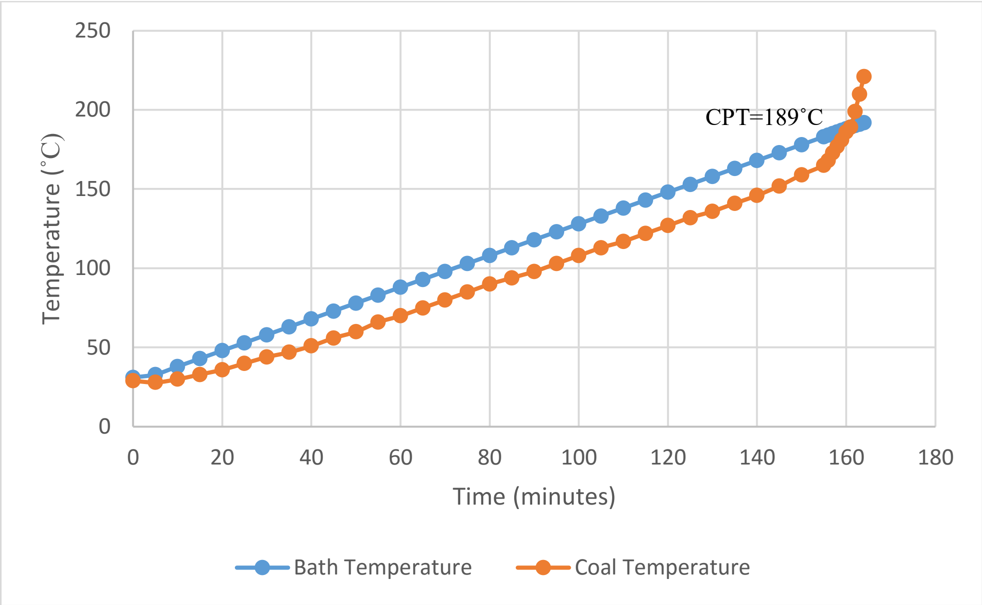

Fig. A-13 CPT Curve of CCL-9

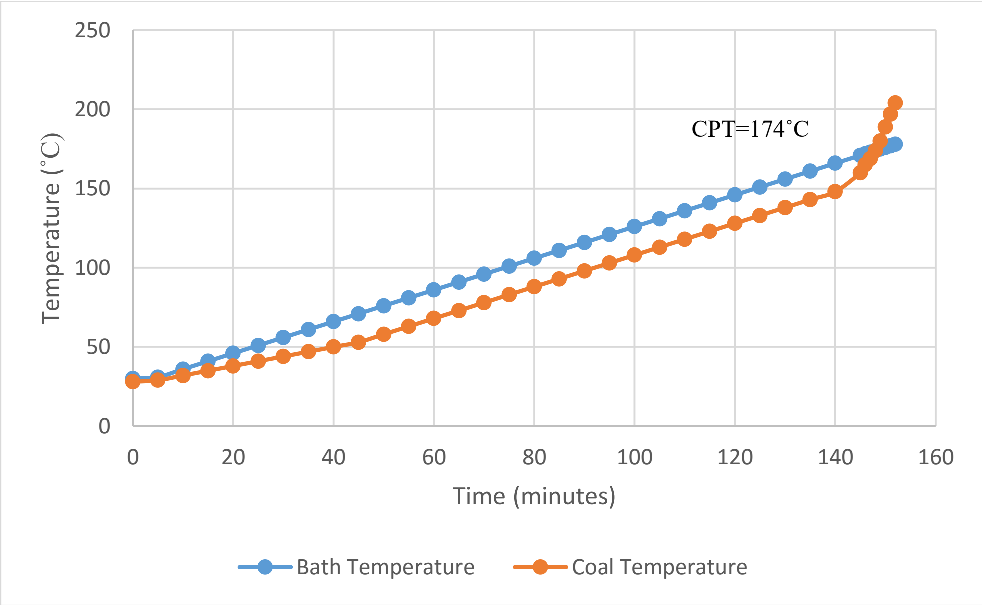

Fig. A-14 CPT Curve of MCL-5

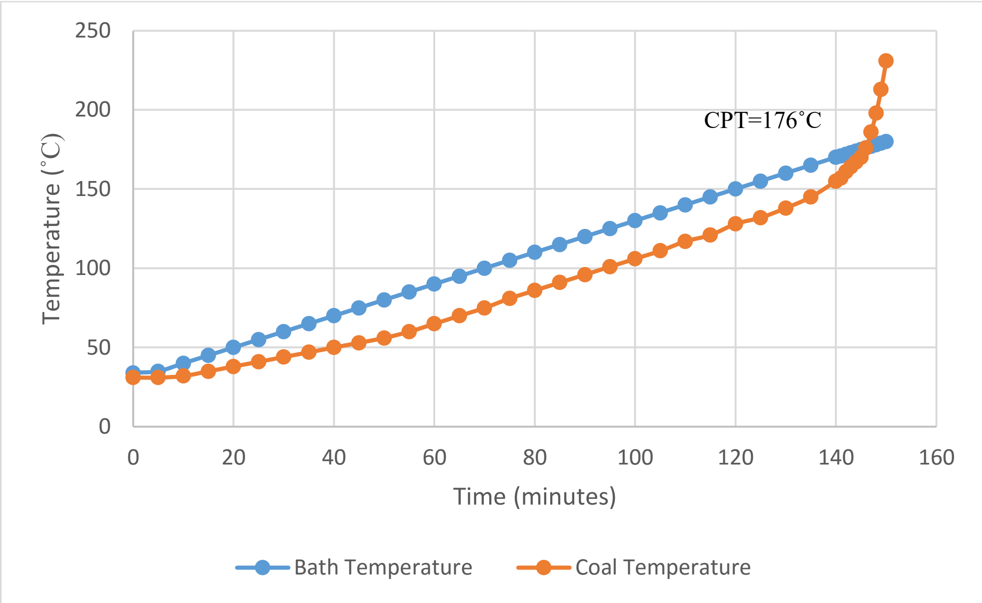

Fig. A-15 CPT Curve of MCL-6

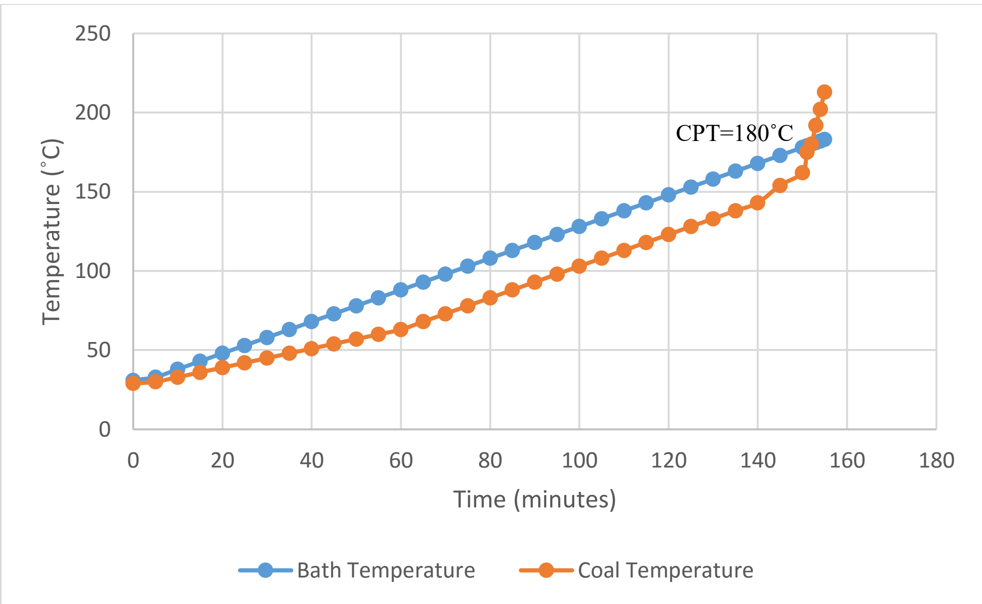

Fig. A-16 CPT Curve of MCL-7

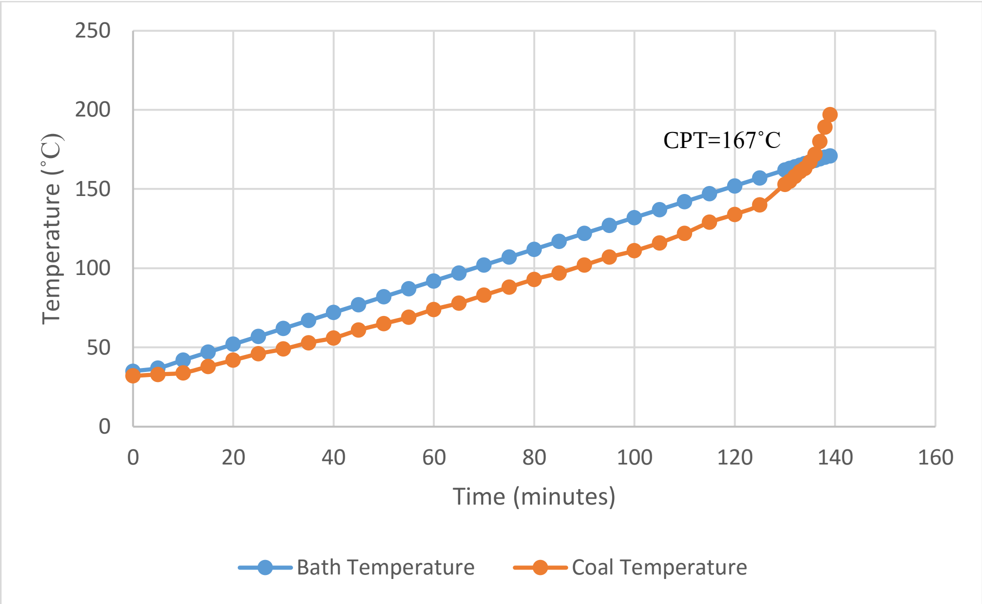

Fig. A-17 CPT Curve of MCL-8

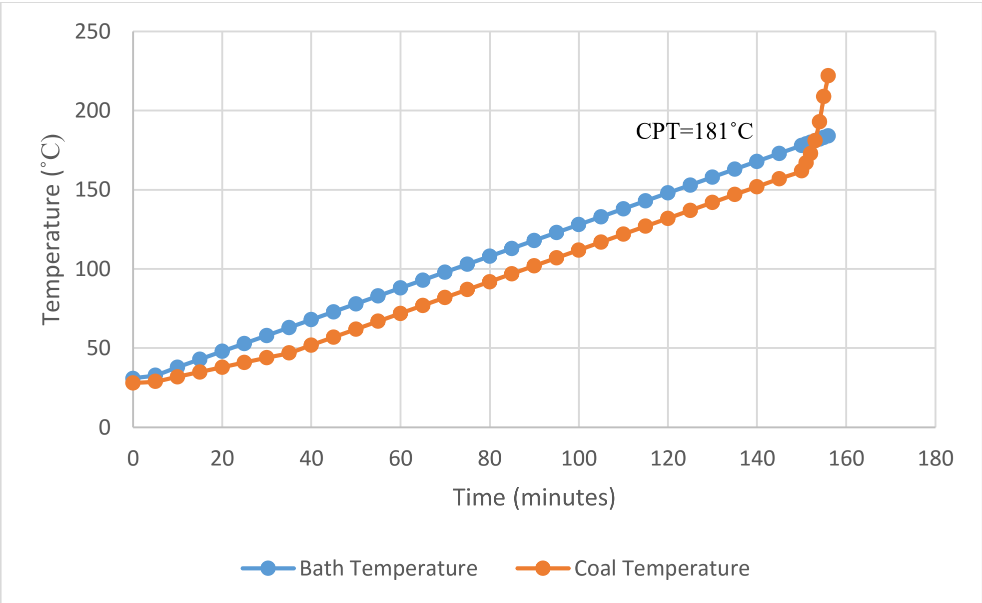

Fig. A-18 CPT Curve of MCL-9

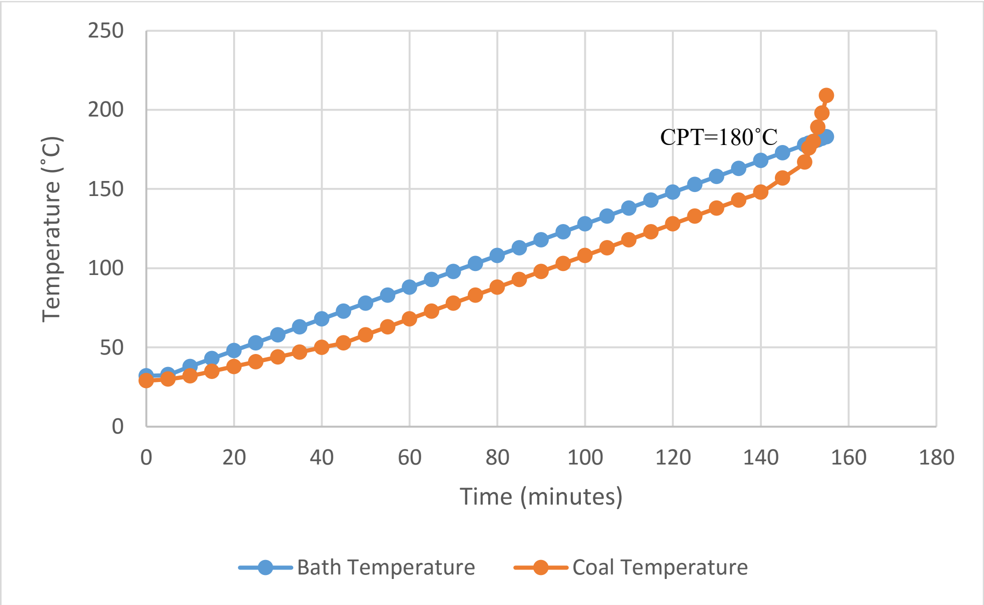

Fig. A-19 CPT Curve of MCL-10

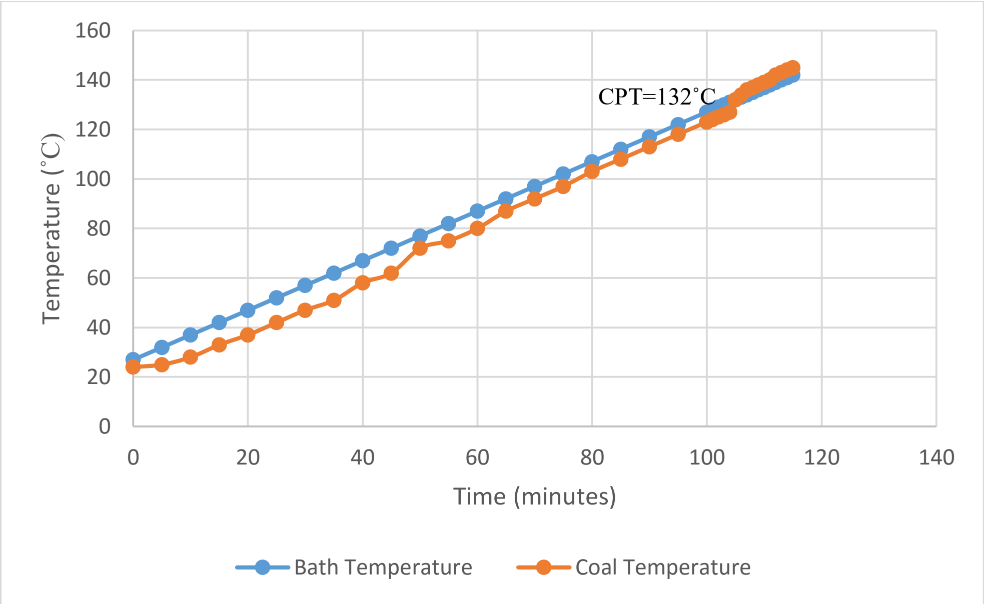

Fig. A-20 CPT Curve of MCL-11